Measuring the Top Yukawa coupling to a heavy Higgs boson at future e^+e^- Linear Colliders

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The determination of the Yukawa coupling of the top quark to the Higgs boson is one of the most important measurements that a future e^+e^- linear collider could provide. For a Higgs boson of mass greater than 350 GeV, this coupling can be determined using the Higgs resonant contribution to $t\bar{t}$ production from W^+W^- fusion at TeV energies. We have made a careful evaluation of the significance with which the signal of a Higgs decaying to $t\bar{t}$ pairs could be observed at future e^+e^- linear colliders, with center of mass energies close to 1 TeV and an integrated luminosity of 1 ab^{-1}. We find that a signal significance greater than 5 σ and a relative error in the top Yukawa measurement better than 10% can be achieved, for Higgs masses in the $350-500$ GeV and $350-650$ GeV ranges at facilities with 800 GeV and 1 TeV energies respectively.

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One of the most important tasks of future particle collider experiments is to investigate the spontaneous breaking of electroweak symmetry and, in particular, to understand the mechanism that generates the masses of elementary particles. In the Standard Model (SM) of electroweak interactions, fermion masses are generated through the Yukawa interactions that couple the fermions to the Higgs field. This mechanism implies that, after spontaneous symmetry breaking, the fermion mass m_f and its coupling y_t to the physical Higgs boson are related by $m_f = y_t v$, where v is the Higgs vacuum expectation value. The experimental verification of this relation by the independent measurement of the fermion masses and their Yukawa couplings provides an essential test of the fermion mass generation mechanism of the SM.

This test has particular theoretical interest in the case of the top quark. Since the mass of the top quark is close to the electroweak scale, it must have couplings of order one to the symmetry breaking sector. Thus it is expected to be a very sensitive probe of possible new physics that might be responsible for generating the top quark mass. For example, alternative models of electroweak symmetry breaking with new strong interactions, like Technicolor and Topcolor models, substantially modify the top quark interaction with the Higgs sector and give rise to new signals that could be studied at future e^+e^- colliders [1]. In spite of the interest of these new physics signals, we will concentrate here on a study within the SM, given the intrinsic importance of the top Yukawa coupling.

Experimentally, the determination of the top quark Yukawa coupling is a challenging measurement that requires future accelerators with the highest center of mass (CM) energies and luminosities. If the Higgs boson mass m_H is below 120 GeV, the top Yukawa coupling could be measured in associated $t\bar{t}H$ production, with a statistical error of the order of 10% both at the CERN LHC [2] and at high energy e^+e^- linear colliders (LC) [3,4]. But associated production is no longer efficient for higher Higgs masses. For a Higgs boson heavier than 350 GeV, the top Yukawa coupling could be determined from the Higgs decay into $t\bar{t}$ pairs. This decay can be studied in high energy e^+e^- colliders using the Higgs resonant contribution to the process $W^+W^- \to t\bar{t}$ [5]. Unfortunately, this electroweak $t\bar{t}$ production process cannot be observed at the LHC, due to the huge QCD background of $t\bar{t}$ production by gluon fusion.

In this letter, we present the results of a complete simulation study of the $W^+W^- \to H \to t\bar{t}$ process at future e^+e^- linear colliders, including realistic backgrounds and experimental effects. The aim is to obtain a reliable evaluation of the significance with which the signal of a Higgs boson decaying to a $t\bar{t}$ pair could be observed, and the accuracy that could be reached in the measurement of the top quark Yukawa coupling through this process at the planned accelerators. We have considered two designs with CM energies of 800 GeV and 1 TeV respectively, assuming an integrated luminosity of 1000 fb^{-1}. Beamstrahlung has been simulated with the program CIRCE [6], using the parameters of the TESLA linear collider [7]. The detector effects have been simulated with SIMDET [8], a fast simulation program which reconstructs energy-flow objects according to the TESLA detector parameters. A similar performance is expected in other accelerator and detector designs, so our results in the framework of the TESLA project also apply to other e^+e^- facilities operating at the same center-of-mass energy and luminosity.

Some care was needed to make an accurate evalua-

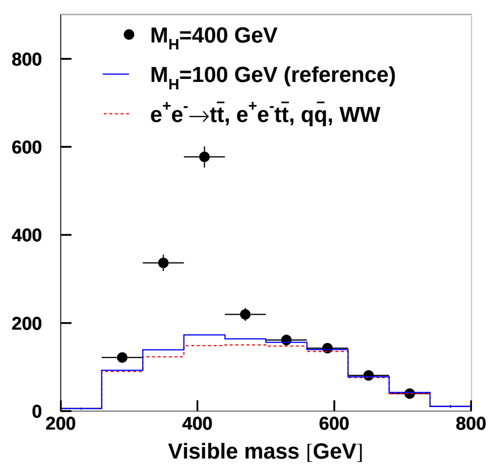

FIG. 1. Expected number of reconstructed 6-jet events as a function of the visible mass, at $\sqrt{s} = 1$ TeV and with $\mathcal{L}$ =1 ab^{-1} after all cuts, for a Higgs boson of 400 GeV (dots) and for the backgrounds (dashed). The expectations (including background) for a Higgs of 100 GeV (solid) are also shown for comparison.

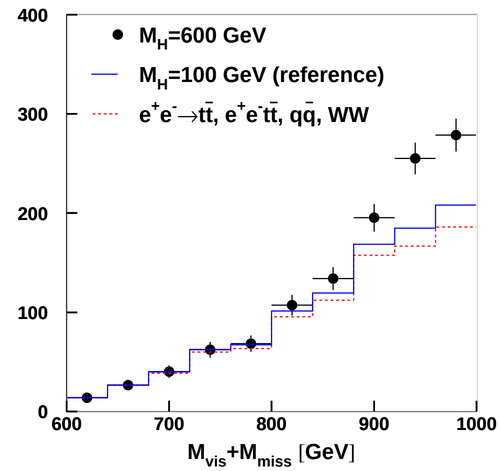

FIG. 2. Sample of reconstructed 6 jet events as a function of the visible plus missing mass, at $\sqrt{s} = 1$ TeV and with $\mathcal{L}$ =1 ab^{-1}. The event numbers correspond to $m_H = 600$ GeV (dots) and the sum of backgrounds (dashed). The expectations for the m_H =100 GeV case (solid) are also shown for comparison.

tion of the $e^+e^- \to t\bar{t}\nu\bar{\nu}$ signal, which includes as a subprocess the WW-fusion reaction $W^+W^- \to t\bar{t}$. We first simulated the signal in the WW-fusion approximation using the event generator Pandora [9]. This calculation was based on the effective-W approximation, using the helicity and p_T-dependent W structure functions of Ref. [10] and on-shell $WW \to t\bar{t}$ scattering amplitudes. Comparing with a full SM calculation using the program CompHep [11] we have found that, at colliders with CM energies of 1.5 TeV or above, the improved WW-fusion calculation approximates well the exact result. However, at energies of 1 TeV or below, the WW-fusion approximation is not reliable, because there are sizeable interference effects between fusion and non-fusion diagrams that give the same $t\bar{t}\nu\bar{\nu}$ final state. Since this effect cannot be neglected or taken into account by adding a reducible, non-interfering background, an event generator including the full $e^+e^- \to t\bar{t}\nu\bar{\nu}$ amplitudes is needed at the CM energies of our study.

To supply this, we have used the computer code NextCalibur [12], an upgraded version of the $e^+e^- \to 4f$ SM generator Excalibur. This new version has an improved simulation of the initial state radiation (ISR) and includes the effects of the finite top mass and the Higgs exchange diagrams which are crucial in our analysis. We had to extend this program to include beamstrahlung effects and to have control on the helicity of the produced $t\bar{t}$ pairs, since the top and antitop decays into the final fermions strongly depend on their polarization state. We then made the top and antitop quarks decay using the routines of Pandora, which fully take into account spin correlations in the $t \to bW \to bff'$ decays and include the finite width effects of the W boson and the top quark. The final hadronization of the decay products was made with PYTHIA [13].

m_H	$\sigma(LL) = \sigma(RR)$	$\sigma(LR)$	$\sigma(RL)$	Total
100	0.11	0.22	0.21	0.65
400	1.89	0.34	0.33	4.45
600	0.89	0.22	0.21	2.21
800	0.33	0.22	0.21	1.09

TABLE I. Helicity cross sections (in fb) for the $e^+e^- \to t\bar{t}\nu\bar{\nu}$ process, at $\sqrt{s} = 1$ TeV and for different Higgs boson masses (in GeV). $\sigma(\lambda, \lambda')$ denotes the cross section for production of a top with helicity λ and an antitop with helicity λ'. CP invariance implies $\sigma(RR) = \sigma(LL)$.

The helicity cross sections for the $e^+e^- \to t\bar{t}\nu\bar{\nu}$ signal process, including ISR and beamstrahlung effects, are given in Table I, for a collider CM energy of $\sqrt{s} = 1$ TeV and different Higgs boson masses. The total signal cross sections range from 0.65 fb for $m_H = 100$ GeV up to 4.45 fb for $m_H = 400$ GeV where the largest sensitivity to the Higgs boson contribution is achieved. The signal events look very much like $t\bar{t}$ events, but with a lower visible mass in general and a substantial missing longitudinal and transverse momenta (of order $M_W/2$) carried away by the two electron neutrinos. Due to the missing momenta in the longitudinal and transverse directions, only the final 6-jet events in which both the top and antitop decay into a b quark plus two additional quarks can be fully reconstructed experimentally. For this rea-

son, we restrict our analysis to events with 6 jets in the final state.

The main backgrounds to this signal have been generated with PYTHIA. There are huge backgrounds from $q\bar{q}$ and W^+W^- production, with total cross sections before cuts of 3400 fb and 3700 fb respectively at $\sqrt{s}$= 1 TeV. Fortunately, they present event shapes very different to the signal, so that they are largely reduced by applying hard cuts. We require no isolated leptons in the final state and force the event into six jets (Durham Algorithm) with Y greater than $5{\times}10^{-4}$. We have also imposed loose cuts in the event thrust, major and C-parameter to reject back-to-back events, and a moderate b-tagging based on consistency with primary vertex.

More dangerous backgrounds are direct $t\bar{t}$ production, with a cross section of 243 fb and $e^+e^-t\bar{t}$ production with 17 fb. This latter background comes mainly from $\gamma\gamma$ fusion and can be reduced requiring the missing transverse energy in the event to be greater than 50 GeV. We have also required missing mass greater than 200 GeV, to suppress $t\bar{t}$ production with ISR and to cut the Z peak from $Zt\bar{t}$ production with the Z decaying into two neutrinos.

After these cuts, there is still too large a contribution from misreconstructed $e^+e^- \to t\bar{t}$ events. This background can be efficiently reduced by choosing the jet association that gives the best fit to the reconstructed t and W masses and keeping events within five standard deviations of the expected values. After all cuts, the acceptances for the signal events are in the range of 18% to 12% for $\sqrt{s} = 1$ TeV and Higgs masses from 400 GeV to 800 GeV. The WW and $q\bar{q}$ backgrounds are largely reduced by a 5×10^{-6} rejection factor, becoming a small percentage of the background composition which is dominated by the $e^+e^- \to t\bar{t}$ and $e^+e^- \to e^+e^-t\bar{t}$ samples.

In order to evaluate the significance of the $W^+W^- \to H \to t\bar{t}$ signal, we have chosen as final reference background the data expectation in the case of a light Higgs boson ($m_H = 100$ GeV). The signal to background ratio strongly depends on the Higgs mass hypothesis. For $m_H = 400$ GeV, we expect a total number of 695 reconstructed 6-jet events for the signal over 993 events of background. This gives a visible mass distribution nicely peaked at the expected Higgs mass value, leading to a significant observation as shown in Fig.1. The situation gets worse as the Higgs mass increases, giving only 52 signal events at $m_H = 800$ GeV. For higher values of m_H, the most sensitive distribution is the sum visible plus missing mass, which strongly peaks at values close to $\sqrt{s}$ when the Higgs boson is produced almost at rest. This distribution is also shown in Fig.2, in the case of $m_H = 600$ GeV.

The results of the analysis are summarized in Figs. 3 and 4 and in Table II. The significance of the signal is estimated by binned fits to the visible and the visible plus missing mass distributions. The measured data in each bin, N, are assumed to follow the dependence $N = x\ S + B$, where S and B are the signal and background expectations, respectively. The significance is given by $x/\delta x$, where x is the fitted factor (1 in the SM) and δx is the statistical error from the fit. The results guarantee that at $\sqrt{s} = 1$ TeV a signal can be observed at the level of 5 standard deviations if the SM Higgs mass is in the $2m_t < m_H < 650$ GeV range. Systematic effects are not expected to modify significantly this result. The signal of a $H \to t\bar{t}$ decay could be established with more than 20 σ if the Higgs boson mass is close to 400 GeV. As expected, the visible mass distribution is more sensitive than the visible plus missing mass distribution for lower Higgs mass values, and the situation is reversed at Higgs masses approaching $\sqrt{s}$. The analysis has been repeated at a lower CM energy of $\sqrt{s} = 800$ GeV. In this case the 5 σ range of observation is reduced to $2m_t < m_H < 500$

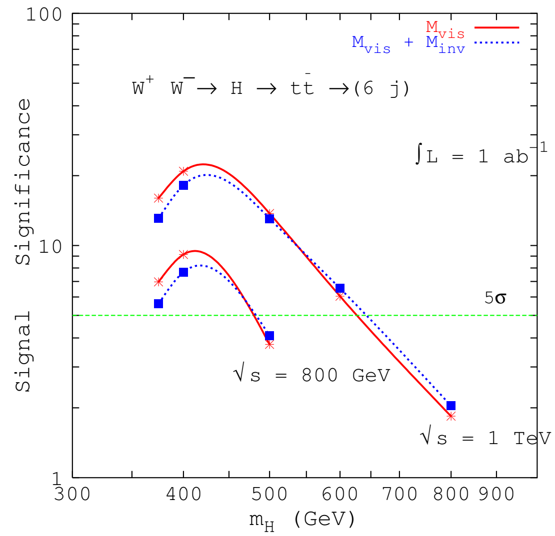

FIG. 3. Expected significance of the $H \to t\bar{t}$ signal as a function of the Higgs mass, from 6-jet events at TESLA.

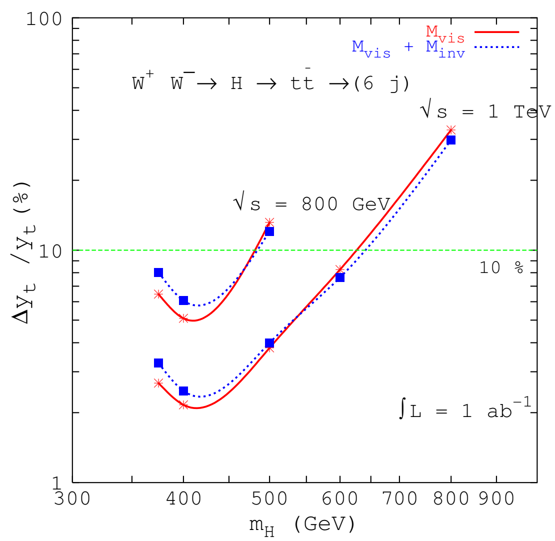

FIG. 4. Expected relative precision in the top Yukawa measurement as a function of the Higgs mass, from 6-jet events at TESLA.

	$\sqrt{s} = 1$ TeV		$\sqrt{s} = 800$ GeV	
m_H	Signif. (σ)	$\Delta y_t/y_t(\%)$	Signif. (σ)	$\Delta y_t/y_t(\%)$
375	16 [13]	2.7 [3.3]	7.0 [5.6]	6.5 [8.3]
400	21 [18]	2.2 [2.5]	9.1 [7.7]	5.1 [6.1]
500	14 [13]	3.8 [4.0]	3.8 [4.1]	13 [12]
600	6.0 [6.5]	8.2 [7.6]	–	–
800	1.8 [2.0]	33 [30]	–	–

TABLE II. Expected significance and relative precision in the top Yukawa measurement for different Higgs masses at TESLA, obtained from the binned fit to the visible mass distribution. The results from the fit to the visible plus missing mass distribution are also given in brackets.

GeV, due to a lower signal cross section and a larger cross section for the $e^+e^- \to t\bar{t}$ background.

The significance of the signal can be reinterpreted as a direct measurement of the $Ht\bar{t}$ Yukawa coupling y_t. These results are presented in Fig. 4 and in Table II. The main conclusion is that, for all cases in which there is a 5 σ evidence for the signal, the Yukawa coupling can be measured with a relative precision better than 10%. A maximum accuracy close to 2% can be achieved for Higgs masses around 400 GeV. It is also remarkable that it would be feasible to establish a non-vanishing Yukawa coupling at the 95% confidence level for masses as high as $m_H = 800$ GeV at a $\sqrt{s} = 1$ TeV collider, provided that the possible sources of systematic uncertainties are kept under control.

To conclude, we have shown that if the Higgs boson is heavier than 350 GeV, it will be possible to establish the signal of the Higgs decaying to top-antitop pairs at future high energy e^+e^- colliders, giving a good determination of the value of the top-Higgs Yukawa coupling. This would be an important measurement that cannot be done at the LHC. The significance of the signal is impressive for a $\sqrt{s}$= 1 TeV collider, and reasonably good at $\sqrt{s}$=800 GeV. It should be remembered that, if the Higgs boson mass is in the $350 - 600$ GeV range, it will be seen first at the LHC through its decay into vector bosons, with significances of the order of $40 - 30$ standard deviations [2] assuming full luminosity of 100 fb^{-1}. The possibility of observing the Higgs decay into $t\bar{t}$ pairs with a similar significance, as given in Table II, is a remarkable and largely unexpected result of our analysis.

The signal significance could be substantially increased using tighter cuts and more sophisticated methods in the event and data analysis. Several tools that depend crucially on an optimal detector performance, like kinematic fitting, a high degree of b or c-tagging, polarization analysis in top decays, etc..., have not been used in this study. This gives our analysis a high degree of robustness, and allows these results, obtained in the framework of the TESLA project, to be safely extrapolated to other e^+e^- accelerator and detector designs. Moreover, we can expect a similar degree of signal observability in other physical scenarios, like Technicolor and Topcolor models, in which new resonances from the symmetry breaking sector give effects of similar strength as the SM Higgs boson contribution.

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